LCA Methodology

Nitrogen Emissions

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Methods to Estimate On-Field Nitrogen Emissions from Crop Production as an Input to LCA Studies in the Agricultural Sector

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Abstract. Nitrogen compounds emitted from the field are usually considered in Life Cycle Assessments (LCA) of agricultural products or processes. The environmentally most important of these N emissions are ammonia (NH_3), nitrous oxide (N_2O) and nitrate (NO_3). The emission rates are variable due to the influence of soil type, climatic conditions and agricultural management practices. Due to considerable financial and time efforts, and great variations in the results, actual measurements of emissions are neither practical nor appropriate for LCA purposes. Instead of measurements, structured methods can be used to estimate average emission rates. Another possibility is the use of values derived from the literature which would, however, require considerable effort compared to estimation methods, especially because the values might only be valid for the particular system under investigation.

In this paper methods to determine estimates for NH_3, N_2O and NO_3 emissions were selected from a literature review. Different procedures were chosen to estimate NH_3 emissions from organic (HORLACHER & MARSCHNER, 1990) and mineral fertilizers (ECETOC, 1994). To calculate the N_2O emissions, a function derived by BOUWMAN (1995) was selected. A method developed by the German Soil Science Association (DBG, 1992) was adopted to determine potential NO_3 emissions. None of the methods are computer-based and consequently require only a minimum set of input data. This makes them, on the one hand, transparent and easy to perform, while, on the other hand, they certainly simplify the complex processes.

Keywords: Agriculture; ammonia; ammonium; crop production; emission factors; estimation methods; fertilizer; LCI; Life Cycle Inventory; nitrogen emission; NH_3; NH_4; nitrate; nitrous oxide; N_2O; NO_3

Introduction

On-field nitrogen (N) emissions are usually considered in LCA studies where agricultural production is part of the investigated system (e.g. production of food). Nitrogen emissions often contribute considerably to the final results of the LCA studies (AUDSLEY et al., 1997; KÜSTERS & JENSSEN, 1998; CEDERBERG, 1998; ANDERSSON & OHLSSON, 1999). However, it is often difficult to derive exact rates of N released to the air and water, because emission rates can greatly vary depending on soil type, climatic conditions and agricultural management practices. Measurements of these emissions require considerable investment in terms of money and time, and they reveal great variations in any case (e.g. ISERMANN, 1990, for NH_3) because they can only reflect a snapshot of

the specific conditions at the time of measurement. For LCA purposes, average potential emission rates adjusted to the conditions typical for the system under investigation would be more appropriate. Methods, however, are required to enable the LCA practitioner to easily calculate potential nitrogen emission rates taking into account important the site-specific parameters. In this study, easy to perform methods or factors are proposed to estimate the most important nitrogen emissions (NH_3, N_2O, NO_3) related to crop production. – Fig. 1 shows a simplified nitrogen cycle focusing on the most important nitrogen in and outputs.
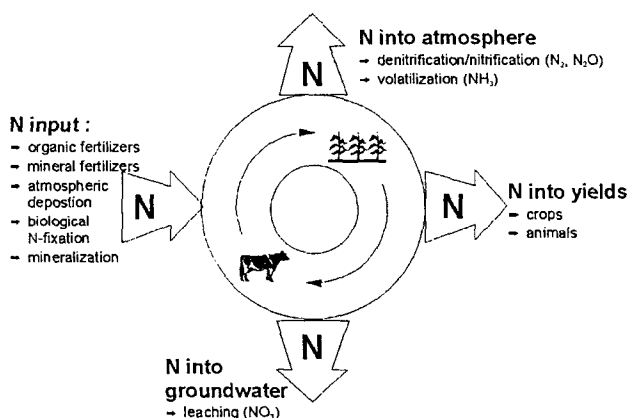

Fig. 1: The nitrogen cycle on a farm (adopted from ECETOC, 1988)

Agriculture, including both crop and animal production, contributes considerably to total NH_3, NO_3 and N_2O emissions. Especially for ammonia, agriculture is by far the main source of emissions. Table 1 provides information about the contribution of agricultural production on the different total nitrogen emissions at different spatial scales.

Table 1: The share of agriculture on total global, European and German N emissions

	Globe	Europe	Germany
NO_3	a	a	50% [b]
NH_3	87% [c]	97% [d]	96% [e]
N_2O	47% [f]	48% [d]	33% [e]

(a) no information
(b) Stanners, 1995
(c) Isermann, 1990
(d) Jol & Kielland, 1997
(e) Enquete-Kommission 'Schutz der Erdatmosphäre', 1994
(f) Kroeze, 1994

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1 Ammonia Volatilization

Nearly 90% of the global emissions of the volatile gas ammonia (NH_3) are related to agriculture (see Table 1). Within agriculture, animal husbandry has by far the greatest share on ammonia released to the environment (ISERMANN, 1990, ECETOC, 1994). Ammonia volatilization occurs during and after the production, storage and application of organic fertilizers (see section 1.1). Mineral fertilizers contribute to a lower extent to the total NH_3 emissions, but show differences, e.g. dependent on the N-form used (see section 1.2). Especially the use of NH_4 and urea containing mineral fertilizers can result in high NH_3 emissions. Unfortunately no estimation method is available that covers both, the NH_3 losses due to organic and to mineral fertilization. Therefore, two different estimation methods were selected to assess the ammonia emissions caused by fertilizer use. – Ammonia losses due to the production and storage of organic fertilizers, such as manure and slurry, are not in the scope of this article as the focus is only on crop production.

1.1 Ammonia volatilization due to organic fertilizer application

According to Isermann (1990) the ammonia losses during and after the application of organic fertilizers ranges from 1 to 100% of the applied NH_4-N. This clearly indicates the need to estimate the NH_3 emissions both site-specific and dependent on agricultural practices. – In the following, an easy-to-perform procedure is presented which has been proposed by Horlacher & Marschner (1990) to assess the ammonia emissions due to organic fertilizer application. In this method four important and easy to get parameters are chosen to assess the ammonia losses:

• Average air temperature
• infiltration rate
• time between application and incorporation or rainfall
• precipitation or incorporation after application

Increasing air temperature results in increasing ammonia volatilization rates (ECETOC, 1994; HORLACHER & MARSCHNER, 1990). The infiltration rate describes the capability of the soil to take up the NH_3/NH_4^+. The infiltration of NH_3/NH_4^+ into the soil reduces the volatilization rate. The amount of volatilized ammonia depends of course on the time the NH_3 is present on the soil surface. Thus, the time between the application and the disappearance of the NH_3/NH_4^+ deeper into the soil profile has to be considered in the estimation (HORLACHER & MARSCHNER, 1990). Rainfall reduces the volatilization of NH_3 considerably due to the increased solution of NH_3/NH_4^+ and an increased infiltration into the soil. The extent of this reduction depends on the amount of rainfall (HORLACHER & MARSCHNER, 1990). Incorporation of the organic fertilizers also reduces the NH_3 losses, as the NH_3/NH_4^+ gets deeper into the soil (SOMMER, 1992).

In the estimation method, the NH_3 losses are calculated as a percentage of the total NH_4-N applied in the form of organic fertilizers. Thus, the NH_4-N content of the applied organic fertilizer should be known. Some average figures are given in Table 2. The original method of Horlacher &

Marschner (1990) is calibrated only for the application of cattle slurry and was tranferred to other forms and origins of organic fertilizers (Table 2). However, it should be noted here that this extension of the original method has not been tested or validated.

Table 2: Dry matter, N and NH_4-N content of different organic fertilizers

Fertilizer typ	Dry matter (%)	N (kg/t)	NH_4-N (kg/t)	NH_4-N (% of N, rounded)
Cattle manure [a]	25	5.0	0.5	10
Cattle slurry [b]	8	4.0	2.2	55
Cattle liquid manure [b]	2	4.0	3.5	85
Calf slurry [b]	3	3.6	2.0	55
Pig manure [a]	23	6.0	0.6	10
Pig slurry [b]	6	5.1	3.6	70
Pig liquid manure [b]	2	5.0	4.5	90
Sow slurry [b]	5	4.1	2.9	70
Chicken slurry [b]	14	8.7	6.0	70

(a) Enquete-Kommission 'Schutz der Erdatmosphäre', 1994
(b) Hydro Agri, 1993

1.1.1 Temperature

The air temperature is a key parameter for the NH_3 volatilization rate. Therefore, the influence of infiltration rate, time period and rainfall on the NH_3 volatilization rate is assessed at different temperature levels. In the following, four classes of temperature are distinguished: 0-5, 5-10, 10-15 and 15-20°C.

1.1.2 Infiltration rate

The infiltration rate can be evaluated according to Table 3. If two evaluation criteria were met, which lead to different infiltration rates, the lower infiltration rate should be chosen, i.e. if, for instance, liquid manure was applied on a heavily compacted soil, the infiltration rate should be regarded as low.

Table 3: Evaluation of the infiltration rate (adopted from HORLACHER & MARSCHNER, 1990)

Infiltration rate	Application circumstances
low	• on cereal or corn stubble • on heavily compacted, water saturated soil • slurry with high dry matter content • solid manure
medium	• on non compacted soil • slurry with medium dry matter content
high	• on prepared soil with a lot of macropores (e.g. ploughed soil) • on loose soil • slurry with low dry matter content • liquid manure

The maximum potential ammonia loss in percentage of the applied NH_4-N is shown in Table 4 for different infiltration rates and temperatures. This maximum potential ammonia loss should be taken as an input parameter for an LCA, if no incorporation or rainfall after application took place.

Table 4: Maximum potential ammonia loss in % of the applied NH_4-N dependent on temperature and infiltration rate into the soil (Horlacher & Marschner, 1990, modified)

Temperature (°C)	NH_3 losses (%)		
	low infiltration	medium infiltration	high infiltration
0 - 5	30	22	15
5 - 10	45	35	25
10 - 15	70	55	40
15 - 20	90	75	55

1.1.3 Time

Incorporation of the organic fertilizer into the soil or rainfall after application leads to a reduction of the maximum potential ammonia loss from **Table 4**. The longer the time period between the application of an organic fertilizer and its incorporation or rainfall, the higher is the ammonia loss. This is considered by multiplying the maximum potential NH_3 loss (see Table 4) by a time factor (Table 5), derived from field experiments (Horlacher & Marschner, 1990). The resulting score represents the actual NH_3 loss between the application of the organic fertilizer and its incorporation or rainfall.

corporation should be considered as ammonia volatilization (Sommer, 1992). The calculation is similar to the calculation for precipitation.

1.1.6 Other factors

Other climatic factors influencing the NH_3 volatilization rate are **radiation** and **wind speed**. High radiation as well as high wind speed lead to increased ammonia losses. These factors are either well enough reflected by already integrated parameters (radiation by temperature) or very difficult to derive (wind speed) (Horlacher & Marschner, 1990). Nevertheless, especially wind speed may have a great influence on the volatilization rate and it would therefore be desirable to take account of this factor (Erisman, 1999). – Soil-related parameters such as **buffer capacity**, **pH** and **cation exchange capacity** have an effect on ammonia volatilization (ECETOC, 1994):

- High pH (>8) → high NH_3 volatilization rate
- high buffer capacity → high NH_3 volatilization rate
- low cation exchange capacity → high NH_3 volatilization rate

Table 5: Time factors for different temperature classes (Horlacher & Marschner, 1990, modified)

Temperature (°C)	Time between application and precipitation / incorporation											
	1h	2h	4h	8h	12h	1d	2d	3d	4d	6d	8d	12d
0 - 5	0.04	0.07	0.10	0.15	0.19	0.25	0.35	0.45	0.54	0.60	0.80	1.00
5 - 10	0.06	0.10	0.14	0.20	0.25	0.35	0.50	0.65	0.73	0.85	1.00	
10 - 15	0.15	0.25	0.35	0.50	0.60	0.73	0.83	0.92	1.00			
15 - 20	0.20	0.30	0.45	0.65	0.75	0.85	0.95	1.00				

1.1.4 Precipitation

Further NH_3 loss depends on the amount of rainfall. This is taken into account by introducing a rain factor (Table 6), which is again based on field experiments (Horlacher & Marschner, 1990). The remaining potential ammonia loss, i.e. the maximum potential loss minus the loss between application of organic fertilizers and rainfall (see section 1.1.3), is multiplied by this rain factor. The resulting figure gives the NH_3 loss after rainfall.

Table 6: Rain factors for different temperature classes (precipitation after application and before total potential volatilization (Horlacher & Marschner, 1990, modified)

Temperature (°C)	Precipitation			
	0 - 2mm	2 - 5mm	5 - 10mm	> 10mm
0 - 5	0.30	0.15	0.05	0
5 - 10	0.40	0.20	0.10	0
10 - 15	0.60	0.40	0.20	0
15 - 20	0.80	0.50	0.30	0

1.1.5 Incorporation

Incorporation of slurry or manure into the soil reduces the ammonia losses to very low rates dependent on the depth of incorporation (Sommer, 1992, Horlacher & Marschner, 1990). Therefore, if the organic fertilizer was incorporated, 2% of the remaining potential NH_3 loss at the time of in-

However, as there is no estimation framework available considering these factors, they are not integrated. This is supported by **Horlacher & Marschner** (1990). According to their findings infiltration is the main soil-related factor.

1.2 Ammonia volatilization due to mineral fertilizer application

The ammonia emissions due to the application of mineral fertilizers are usually lower compared to slurry and manure (Isermann, 1990). However, dependent on the ammonium and urea content of a mineral fertilizer, the climatic conditions and soil properties, considerable ammonia volatilization can also take place when applying mineral fertilizers. The ECETOC (1994) proposed a method to estimate these emissions taking into account the different soil properties throughout Europe and the different NH_3 volatilization risk dependent on the fertilizer type. They defined three classes of countries with different regional sensitivity to NH_3 volatilization (Table 7).

Table 7: European countries grouped according to their NH_3 volatilization sensitivity

Group	Countries	Calcareous soil	pH (usually)	Sensitivity
I	GR, E	common	> 7	high
II	I, F, UK, IRL, P, B, NL, L	partly existent	7	medium
III	N, S, FIN, DK, D, CH, A	rare	< 7	low

Based on a literature review, ECETOC (1994) developed NH_3 emission factors for six groups of mineral fertilizers taking into account the regional differences in NH_3 volatilization sensitivity. The resulting emission factors are shown in Table 8. These emission factors are also supported by many field trials, as for instance reviewed by Wiesler (1999).

Table 8: Emission factors (% NH_3-N loss of total applied mineral N) for different mineral fertilizers in Europe (ECETOC, 1994, modified)

Fertilizer type	Groups of European countries (according to Table 10)		
	Group I	Group II	Group III
Urea	20	15	15
Ammonium Nitrate, Calcium Ammonium Nitrate, NP, NK, NPK	3	2	1
Ammonium Phosphate	5	5	5
Ammonium Sulphate	15	10	5
Anhydrous Ammonia	a	a	4
Urea Ammonium Nitrate solution	8	8	8

(a) fertilizer not common in this group of countries

An incorporation of mineral fertilizer into the soil should be considered. In this case it is proposed to take the ammonia loss related to the application of ammonium nitrate, i.e. 1-3% of the total amount of nitrogen applied.

2 Nitrous Oxide Emissions

Agriculture has a considerable share on the anthropogenic N_2O emissions (33-48%, see Table 1), whereas N_2O itself contributes to 5% to the total global warming potential. – Nearly 80% of the N_2O emissions due to agriculture are related to the use of mineral and organic fertilizers. Biomass burning (e.g. shifting cultivation, deforestation) is responsible for about 20% (Kroeze, 1994). Two microbial processes in soil are responsible for most of the N_2O emissions in agriculture: Denitri-

fication ($NO_3 \rightarrow NO_2 \rightarrow NO \rightarrow N_2O\uparrow \rightarrow N_2\uparrow$) and nitrification ($NH_4 \rightarrow [N_2O\uparrow] \rightarrow NO_2 \rightarrow NO_3$).

Anaerobic conditions are a prerequisite for N_2O emissions due to denitrification. Furthermore, the available amount of nitrogen in the soil is a decisive factor for the rate of N_2O released. As denitrifying microorganisms need organic carbon as an energy source, the availability of degradable organic matter is a further limiting factor for N_2O formation.

A lot of complex interactions between soil and climate-related factors, on the one hand, and parameters determined by agricultural management, on the other, influence the N_2O emissions. Table 9 summarizes the findings of Granli & Bøckman (1994) concerning these factors.

Dependent on these parameters and their interactions, measurements of N_2O emission from different types of agricultural land show great variations (Granli & Bøckman, 1994).

This clearly indicates a need for taking this variability of N_2O fluxes into account, when estimating N_2O emissions in agricultural Life Cycle Assessment. Unfortunately the complexity of the interactions between the various parameters is up to now not well enough understood to propose an estimation or even calculation method for N_2O emissions (Enquete-Kommission 'Schutz der Erdatmosphäre', 1994). Despite this, Bouwman (1995) proposed an emission factor for N_2O emissions from mineral and organic fertilizers. From field experiments, he derived the following formula:

N_2O emission [kg N_2O-N*ha^{-1}] =
0.0125 * N application[a] [kg N*ha^{-1}]　　　　　　(1)

[a] the applied N rate should be corrected for NH_3 emissions, as these predominantly occur earlier than the N_2O emissions (Kroeze, 1994).

This emission factor of 0.0125 kg N_2O-N*ha^{-1} per kg N input is also taken as a default value for estimating direct nitrous oxide emissions from arable land by the IPCC (Houghton et al., 1997). The Bouwman formula is com-

Table 9: Key parameters influencing N_2O emissions from agricultural soils

Parameter	Effect on N_2O emissions
Soil aeration	• intermediate aeration -> highest N_2O production • low aeration -> high denitrification rate, but mainly N_2 production
Soil water content	• increasing soil water content -> increasing N_2O emissions, but • under very wet conditions -> decline • changing conditions (dry/wet) -> highest N_2O production
Nitrogen availability	• increasing NO_3/NH_4 concentrations -> increasing N_2O emissions
Soil texture	• from sand to clay -> increasing N_2O emissions
Tillage practice	• ploughing -> lower N_2O emissions • no/low-tillage -> higher N_2O emissions
Compaction	• increasing compaction -> increasing N_2O emissions
Soil pH	• where denitrification is main source of N_2O emission: increasing pH results in decreasing N_2O emissions • where nitrification is main source of N_2O emission: increasing pH results in increasing N_2O emissions
Organic material	• increasing organic carbon content -> increasing N_2O emission
Crops and vegetation	• plants, but especially their residues and remaining roots after harvest increase N_2O emission
Temperature	• increasing temperature -> increasing N_2O emission
Season	• wet summer -> highest N_2O production • spring thaw -> high N_2O production • winter -> lowest N_2O emission

monly used, because it is not yet possible to consider the other key parameters (see Table 9) appropriately. It is therefore suggested to use this approach for estimating the nitrous oxide emissions caused by agricultural practice.

Although the N_2O emissions are in the focus of most research activities dealing with denitrification, N_2 is the main product of denitrification and usually released in much higher rates (WIESLER, 1999). N_2 is not of environmental relevance, but N_2 rates emitted to the air should be included in the nitrogen balance, which is a prerequisite for the calculation of the nitrate leaching rate (see section 3, Table 10). Von Rheinbaben (1990) reviewed and evaluated 38 field experiments and concluded that an average of 10% of the fertilizer input is lost as N_2O plus N_2 on arable and grassland. On the other hand, agricultural practices, soil and climate parameters may greatly influence the N_2 emissions as well as that of N_2O. For practical reasons, the N_2-N emissions related to fertilizer application (corrected for NH_3-N volatilization) may be regarded as 9%, taking into account the IPCC emission factor of 1.25% for N_2O-N.

3 Nitrate Leaching

The mineral nitrogen in the soil is mainly nitrate (NO_3^-) and to a lower extent ammonium (NH_4^+). As nitrate is hardly adsorbed by soil particles, it can be easily leached into the groundwater. During the vegetation period, the risk of NO_3 leaching is low because large amounts of nitrate are taken up by the plants. Furthermore, almost no downward water movement occurs during the vegetation period mainly due to high evapotranspiration rates. During the vegetation-free period from late autumn to early spring precipitation often exceeds evapotranspiration so that the mobile NO_3 anion can be leached downwards in the soil.

For LCA purposes it is important to be able to predict the potential NO_3 leaching rate related to an agricultural product or production process. The level of nitrate leaching depends strongly on different parameters. The most important parameters determining the nitrate leaching rate are:

- Agriculture-related: nitrogen balance [kg $N^* ha^{-1} * a^{-1}$]
- Soil-related: field capacity in the effective rooting zone (FC_{RZe}) [mm]
- Climate-related: drainage water rate (W_{drain}) [mm$^* a^{-1}$]

3.1 Agriculture-related parameters

The **nitrogen balance** can be used as a measure for the amount of nitrate-N in the soil susceptible to leaching after the vegetation period in autumn. The nitrogen balance can be calculated as described in **Table 10**.

Table 10: Calculation of the nitrogen balance in autumn

N input [kg $N^* ha^{-1}$]	N output [kg $N^* ha^{-1}$]
+ Mineral N fertilizer	- N removal with harvested crops
+ Organic N fertilizer	
+ Biological N fixation	- NH_3-N emissions
+ Atmospheric N deposition	- N_2O-N / N_2 emissions
+ N mineralization	- N immobilization
Σ input	Σ output
N balance = Σ input - Σ output	

Some of the nitrogen inputs and outputs are already known, as they are either part of the system under investigation (e.g. fertilizer rate, crop removal) or have been already estimated (e.g. NH_3-N, N_2/N_2O-N). If fertilizer rates or crop removals are unknown, typical figures for the different crops and agricultural production systems should be available at least for European countries (for Germany: e.g. Hydro Agri, 1993). Regarding the biological N fixation, for instance, Loges et al. (2000) presented a model for the quantification of N_2 fixation of legumes.

The deposition of nitrogen from the atmosphere should also be accounted for when estimating the amount of nitrate in the soil susceptible to leaching during autumn and winter. The N input due to the wet and dry deposition of oxidised and reduced nitrogen compounds is not directly influenced by the product or process under investigation. However, the deposited nitrogen may enter the system as it can be taken up by the plants, similar to mineral fertilizers. **Fig. 2** provides information about the N deposition rate in Europe.
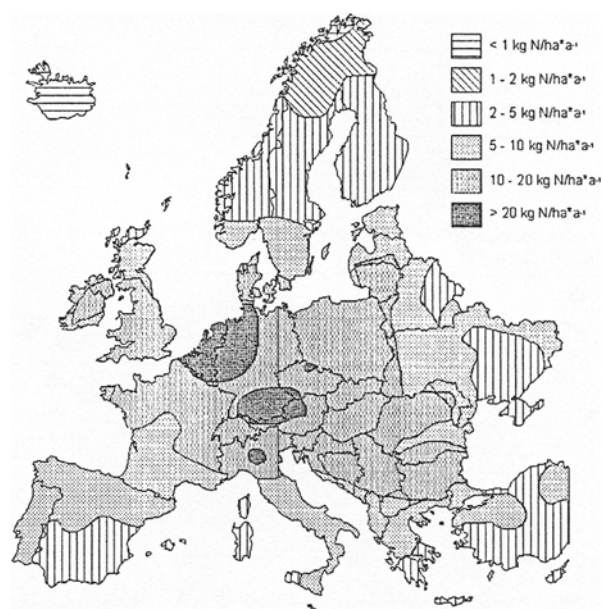

Fig. 2: Total nitrogen deposition in Europe in 1993 (adopted from Umweltbundesamt, 1997)

Based on the assumption that an agricultural production system is relatively constant long term, i.e. for more than one crop rotation, and that the N fertilizer input is adjusted to the requirements of the plants, it can be assumed that the nitrogen mineralization and immobilization rates more or less equal each other (ENGELS, 1993). Some other agricultural aspects can influence the nitrogen balance considerably. For example **intercropping** as well as **underseeding** may reduce the nitrogen amount in autumn by more than 40% (SCHEFFER & ORTSEIFEN, 1996).

That part of the nitrate-N present in the soil in autumn that is actually lost via leaching depends on soil and climate parameters. The influence of these parameters is described and quantified in the following sections.

3.2 Soil-related parameters

The field capacity in the effective rooting zone (FC_{RZe}) describes the capacity of the soil to adsorb water within that part of the soil in which the roots are able to take up water. The FC_{RZe} can be calculated by multiplying the available field capacity (FCa) by the effective rooting zone (RZe).

$$FC_{RZe} \text{ [mm]} = FCa \text{ [mm*dm}^{-1}\text{]} * RZe \text{ [dm]} \qquad (2)$$

The available field capacity as well as the effective rooting zone strongly depends on the soil texture. The German Soil Science Association (1992) proposed six classes of available field capacity (Table 11) and five classes of effective rooting zone (Table 12).

Table 11: Assignment of soil textures to 6 classes of available field capacity (FCa), medium soil density (DBG, 1992)

Class	Soil texture*	FCa (mm*dm⁻¹)	
(evaluation)		range	average
1 (very low)	S	< 10	8
2 (low)	lT	10 – 14	12
3 (medium)	lS, tS, sL, tL, uT, T	14 – 18	16
4 (high)	uS, sU, uL	18 – 22	20
5 (very high)	lU, tU, U	> 22	24
6 (swamp)	Hh, Hn		60

(a) S = sand, s = sandy, U = silt, u = silty, T = clay, t = clayey, L = loam, l = loamy, H = swamp, h = swampy, n = half-swampy

Table 12: Assignment of soil textures to 5 classes of effective rooting zone (RZe), medium soil density (DBG, 1992)

Class	Soil texture*	RZe (dm)	
(evaluation)		range	average
1 (very low)	Hn	< 3	2
2 (low)	S, Hn	3 – 5	4
3 (medium)	lS, uS	5 – 7	6
4 (high)	tS, lS	7 – 9	8
5 (very high)	U, sU, lU, tU, sL, uL, tL, lT, T	> 9	10

(a) S = sand, s = sandy, U = silt, u = silty, T = clay, t = clayey, L = loam, l = loamy, H = swamp, h = swampy, n = half-swampy

Hence, to calculate the field capacity in the effective rooting zone (FC_{RZe}), only information about the soil texture is needed.

3.3 Climate-related parameters

The rate of drainage water (W_{drain}) is mainly determined by the precipitation rate (W_{precip}), its distribution through the year and the evapotranspiration rate. The drainage water rate can be either measured or estimated according to Formula (3), as developed by Liebscher & Keller (1979, in DBG, 1992). This approach is based on regression analysis and is suitable for flat lands. Bach (1987) found a good correlation between values calculated according to formula (3) and his own measurements.

$$W_{drain} \text{ [mm]} = 0.86 * W_{precip\_year} \text{ [mm]} - 11.6 *$$

$$(W_{precip\_summer} / W_{precip\_winter}) \text{ [mm]} - 241.4 \qquad (3)$$

The precipitation rate for the hydrologic summer (04-01 to 09-30) and the hydrologic winter (10-01 to 03-31) should be easily available (e.g. for Germany: Deutscher Wetterdienst).
– The nitrate leaching rate is mainly dependent on the quantity of water that percolates through the soil profile into the groundwater. A measure for this quantity is the exchange frequency of the drainage water per year. This can be calculated using FC_{eRZ} (2) and W_{drain} (3) as input parameters.

$$\text{exchange frequency } * \text{ a}^{-1} = W_{drain} \text{ [mm*a}^{-1}\text{]} * FC_{RZe}^{-1} \text{ [mm]} \quad (4)$$

Due to the fact that almost all NO_3 in the soil is dissolved in water, the whole amount of NO_3-N present in the soil at the beginning of the leaching period in autumn is supposed to be available for leaching. The exchange frequency of the drainage water directly reflects the share of nitrate lost via leaching. If the exchange frequency per year is equal or higher than 1, the whole amount of nitrate is supposed to be leached. Therefore, the maximum value for the exchange frequency per year used in (5) is 1.

$$\text{leached } NO_3\text{-N [kg N*ha}^{-1}*\text{a}^{-1}\text{]} =$$
$$NO_3\text{-N}_{in\,soil\,in\,autumn} \text{ [kg N*ha}^{-1}\text{]} * \text{ exchange frequency } *\text{a}^{-1} \quad (5)$$

4 Example

In the following, an LCA case study on winter wheat production (KÜSTERS & JENSSEN, 1998) is chosen to illustrate the calculation procedures given in the previous sections. The winter wheat system is located on a farm in northern Germany and the yield is 8.5 tonnes of grain per ha. The straw (8 tonnes/ha) is baled and removed from the field. The N fertilization was 80 kg N/ha as cattle slurry for the first dressing (containing 44 kg NH_4-N/ha) and 130 kg N/ha as ammonium nitrate (AN) for topdressing. The field has been fertilized long-term with slurry.

4.1 Ammonia volatilization

Parameters to calculate the NH_3–N volatilization from cattle slurry:
- Temperature during and after application: 10-15°C
- Infiltration rate: medium (medium dry matter content of the slurry, non compacted soil, see Table 3)
- Precipitation after application: no
- Incorporation of the slurry: yes
- Time between application and incorporation: 4 h

Calculation:
- Maximum potential ammonia loss [% of applied NH_4-N] (see Table 4): 55%
- Multiplication with time factor (see Table 5): 55% * 0.35 = 19.25%, i.e. 19.25% of the applied NH_4-N is lost between application and incorporation (= 8.5 kg NH_3-N/ha)
- 44 – 8.5 = 35.5 kg NH_4-N/ha remains on the field after incorporation
- 2% of this 35.5 kg NH_4-N/ha were lost after incorporation (= 0.7 kg NH_3-N/ha)
- total NH_3-N volatilization due to application of cattle slurry: 8.5 + 0.7 = 9.2 kg NH_3-N/ha

Parameters to calculate the NH_3–N volatilization from mineral fertilizer:
- Type of mineral fertilizer: ammonium nitrate (AN)
- Location of the crop production: Germany

Calculation:

- 130 kg AN-N * 1% = 1.3 kg NH_3-N/ha (see Tables 7 and 8)

4.2 Nitrous oxide emissions

Parameters to calculate the N_2O-N emissions from fertilizer use:

- Total N rate applied per ha: 130 kg N/ha (AN), 80 kg N/ha (slurry)
- NH_3-N losses per ha via volatilization: 10.5 kg NH_4-N/ha

Calculation:

- 130 kg AN-N/ha + 80 kg slurry-N/ha – 10.5 kg NH_4-N/ha = 199.5 kg N/ha
- 199.5 kg N/ha * 0.0125 = 2.5 kg N_2O-N/ha
- Total N_2O-N emission due to fertilizer application: 2.5 kg N_2O-N/ha
- (N_2-N emission: 199.5 kg N/ha * 0.09 = 18 kg N_2-N/ha)

4.3 Nitrate leaching

Parameters to calculate the NO_3 leaching due to fertilizer use:

- Nitrogen inputs [kg N/ha]: mineral and organic fertilizers: 210, biological N fixation: none, atmospheric N deposition: 25, N net-mineralization: 0
- Nitrogen outputs [kg N/ha]: N removal with harvested crops: 153 (grain) + 40 (straw), NH_3-N, N_2O-N and N_2-N emissions: 10.5 + 2.5 + 18
- Soil texture: loamy silt (IU)
- Average precipitation per year: 738 mm, summer: 387 mm, winter: 351 mm

Calculation:

- Nitrogen balance [kg N/ha]: 210 + 25 – 153 – 40 – 10.5 – 2.5 – 18 = 11
- Field capacity in effective rooting zone: 240 mm (see Tables 11 and 12)
- Rate of drainage water [mm per year]: 0.86 * 738 – 11.6 * (387 / 351) – 241.4 = 380
- Exchange frequency of drainage water per year: 380 mm/year * 240 mm = 1.58/year
- NO_3 leaching rate: 11 kg NO_3-N/ha * 1/year = 11 kg NO_3-N/ha/year

5 Comparison of the Methods to Others Used in Recent LCA Studies

In order to compare these models to those used in other LCA studies, the proposed methods have been applied to a wheat production system described by Audsley et al. (1997). In this study, each of four teams of LCA experts from different countries (Denmark, the Netherlands, United Kingdom, Switzerland) examined the environmental impacts of an intensive winter wheat production system located in the UK. In this system, three different mineral fertilizers at a total rate of 240 kg N/ha and no manure were applied. For further details see Audsley et al. (1997). The research teams used different methods to estimate the on-field emissions of ammonia, nitrous oxide and nitrate. Table 13 gives the estimated emission rates of the different teams in comparison to our own estimates.

Table 13: Estimates of on-field emissions of NH_3, N_2O and NO_3 due to an intensive wheat production system (Audsley et al., 1997) calculated with different models

	NH_3 [kg N/ha]	N_2O [kg N/ha]	NO_3 [kg N/ha]
DK models	-[a]	-[a]	44
NL models	4.8	4.0	21
UK models	-[a]	3.1	31
CH models	12.4	7.2	108
Own models	13.2	2.8	32

(a) no estimation carried out

In the following, the main differences between the models described in Audsley et al. (1997) and those proposed in this paper are discussed.

5.1 Ammonia volatilization

- DK and UK team: NH_3 losses were not estimated.
- NL team: One uniform emission factor for all types of mineral N fertilizers was used independent of the site of application (2% of the fertilizer-N as NH_3-N).
- CH team: Emission factors developed by Asman (1992, in Audsley et al., 1997) were used. These factors differ between fertilizer types, but not between sites of application.
- Our own model: Emission factors developed by ECETOC (1994) were applied, which are different dependent on the fertilizer type and the site of application. The factors are based on a broad literature review.

5.2 Nitrous oxide emissions

- DK team: N_2O emissions were not estimated.
- NL team: N_2O emissions were estimated according to Bouwman (1995). The background emission of 1 kg N_2O-N/ha is included, although this is not due to the fertilizer application in the analysed wheat production system. Furthermore, the NH_3-N losses were not subtracted from the N fertilizer rate, which is the basis for the calculation of the N_2O emission rate according to Bouwman (1995) (see Formula (1)).
- UK team: Emission factors from Amstrong-Brown (in Audsley et al., 1997) were used, which are different dependent on the N form and time of application. The reference given is unpublished and therefore the basis for the emission factors is unknown (field experiments, pot trials, literature study?).
- CH team: A uniform emission factor of 3% of the totally applied fertilizer N (BUWAL, 1994, in Audsley et al., 1997) was used, which appears to be relatively high compared to values recommended in the literature (e.g. Kaiser et al., 1996; Bouwman, 1995).
- Our own model: N_2O emissions have been estimated according to Bouwman (1995). The background emission (1 kg N_2O-N/ha) is excluded and the NH_3 losses were subtracted from the rate of N fertilizer applied, as these predominantly occur before the N_2O emissions (Kroeze, 1994).

5.3 Nitrate leaching

- **DK team:** The basis for the estimation is an average NO_3 leaching rate on sandy and loamy soils determined for fertilizer rates according to official recommendation in Denmark (SIMMELSGAARD, 1991, in AUDSLEY et al., 1997). This relationship was used to calculate the NO_3 leaching at any given fertilizer rate. As the reference leaching has been determined under Danish conditions, this may not be representative for conditions in other European regions. Furthermore, the yield level and specific soil and climatic conditions of the analysed system were not accounted for.

- **NL team:** Leaching factors for sandy soils (40.5% of the mineral N remaining in the soil after harvest; GOOSSENSEN & MEEUWISSEN, 1990, in AUDSLEY et al., 1997) and clay soils (20% of the mineral N remaining in the soil after harvest; BREEUWSMA et al., 1987, in AUDSLEY et al., 1997) were used. No further soil and climatic parameters were considered. In the calculation of the mineral N remaining in the soil after harvest, the atmospheric N deposition for NL was used, which may be different for the UK.

- **UK team:** A so-called 'crop/soil/fungicide simulation model', which uses e.g. daily weather records, inputs of mineral and organic N, and soil parameter as input data, was used to determine the leaching rate. As no reference is given, it is not known which other input parameter are necessary to run this model, but computer-based simulation models most often need a lot of very specific input data, which is not always readily available (ENGEL et al., 1993).

- **CH team:** According to a method developed by Walther (1995, in AUDSLEY et al., 1997), the NO_3 leaching rate is supposed to be the sum of (a) the difference between N mineralization and N uptake by the crop, and (b) the N rate applied multiplied by crop specific leaching factors. Both figures are calculated on a monthly basis. As N immobilization processes are not considered, the nitrate content in the soil may be overestimated. Furthermore, the crop-specific leaching factors were estimated for fertilizer rates recommended in Switzerland and, therefore, may be not valid for other fertilizer application rates.

- **Our own model:** The NO_3 leaching rate is calculated from the NO_3-N remaining in the soil after harvest, taking into account specific soil and climate parameters.

6 Conclusions

The first step in a Life Cycle Assessment is to make an inventory of all relevant environmental interventions caused by the system under investigation. For agricultural LCAs, the emissions of ammonia, nitrous oxide and nitrate are usually important and need to be considered. Three ways of taking these nitrogen emissions into account are possible:

- To measure actual emission rates caused by the system under consideration,
- to use values derived from literature in a case-by-case procedure,
- to estimate potential emission rates using structured estimation methods.

To measure actual N emission rates is money and time-consuming and therefore often not operationable in Life Cycle Assessments. Furthermore, actual measurements of N emissions often show great variations (e.g. ISERMANN, 1990, for NH_3) and may reflect only a snapshot of the specific conditions at the time of measurement. For LCA purposes, average emissions adjusted to the conditions typical for the system under examination are therefore more appropriate than actual emission rates.

Values derived from the literature often reflect an average emission, which is assumed to be representative for the system examined in the LCA. A disadvantage to this procedure is that a new literature review might be necessary for each new study in order to obtain new, appropriate values. Furthermore, it is difficult to evaluate the quality of the derived figures as they strongly depend on the quality of the literature source.

An alternative procedure is to use **structured** methods for the estimation of average emission rates. Conditions which influence the nitrogen emissions are reflected by certain parameters (soil, climate, agricultural practice). These parameters should be available and used as an input for the estimation methods. Advantages of such procedures are their easy performance, less effort compared to measurements or values derived from the literature and the comparability of the results. The quality of the estimated emission rates might be improvable, because estimation methods simplify the complex conditions leading to the release of emissions into the environment. Only a limited number of well-know factors are taken into account, assuming that these are the most important ones. However, the presented estimation methods could provide useful tools to obtain reasonable nitrogen emission data for a Life Cycle Inventory in the agricultural sector.

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1st Int. Conference on Tribology in Environmental Design (TED), 4-6 September 2000

The focus of TED2000, which was organised by the Sustainable Product Engineering University Research Centre within Bournemouth University of the UK, was to bridge the gap between the well-studied scientific discipline of tribology and environmental design. Professor H Peter Jost (known by many as being the *Father of Tribology*) described this event as a courageous achievement in raising awareness on the importance that this engineering discipline maintains on the challenges of today.

Throughout the three days of the conference 34 contributions were presented to 50 people from 15 different countries. During his opening address, Sir Gordon Higginson emphasised that these statistics alone made this first event a success when compared to previous tribology events.

Other opening addresses came from Mr. Gordon Waddington, Research and Technology, Rolls-Royce plc of the UK and Professor Stathis Ioannides, SKF Group Technical Development of The Netherlands. Both addresses presented an industrial perspective towards the general scope of the conference. Mr. Waddington emphasised the importance the research topics discussed during TED2000 have to Rolls-Royce. Similarly, Professor Ioannides elaborated on the importance SKF, the largest rolling element manufacturer, sees between tribology and the environment. SKF manufactures 60 billion steel bearings per annum weighing in excess of 4.5 tonnes. Since 1981, SKF managed to half the weight of each bearing saving approximately 90 gigawatts of process electrical energy.

The first day of the conference focused on how to handle wear data and re-use this data as knowledge towards the design of *Life-oriented Products* using *Product Life Design Tools*. Throughout this day an emphasis as to how to address the environment and yet satisfy tribological constraints was highlighted. Frameworks to utilise wear information during the product development phase or in the development of disassembly-friendly products were presented. Fi-

nally, studies on *Life-cycle Assessment for Optimised Products* were presented to characterise the implications tribological issues have during the whole product life cycle.

The second and the third day of the conference focused primarily on the measurements of wear, cutting processes, materials, etc. The topics covered included *Surface Engineering, Lubricants, Test Methods, Advanced Materials* and *Analytical Studies*. Coatings and their applications were discussed and how these may be used to address environmental criteria. Test methods to improve product lifetime or the manufacturability of components were discussed. Advanced materials such as metal composites, silicon nitride and thermoplastics were evaluated and their performance assessed.

The conference was brought to a close by Professor John Tripp of SKF who emphasised that in order to support *Green Things* the slogan *Conserve Energy* must change to *Conserve Entropy*. He emphasised that the principal difference between the two is that the former is a must, anything different would violate the First law of Thermodynamics. The latter, on the other hand, is in accordance with the Second Law of Thermodynamics and characterises the performance of thermal processes and heat engines. To ensure the conservation of entropy industry must *listen* to tribologists, who are constantly dealing with the phenomena of surfaces at nano-scale, micro-scale and contact phenomena.

The enthusiastic comments received throughout the three days led the organisers to believe that TED events may fulfil the tasks they set out to achieve and gain acceptance in the scientific fields of tribology and design.

We look forward to the next conference in Malta.

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